peer reviewed

RESEARCH ON EFFICIENT DRIVING METHOD OF HEAVY HYDRAULIC EXCAVATOR BOOM

Lianpeng Xia, Long Quan*, Lei Ge, Yunxiao Hao, Bin Zhao, Bin Li

Key Lab of Advanced Transducers and Intelligent Control System of Ministry of Education and Shanxi Province, Taiyuan University of Technology, Xikuang Street 53#, 030024 Taiyuan, China

* Corresponding author: Tel.: +86 0351 6014551; E-mail address: quanlong@tyut.edu.cn

ABSTRACT

There is a lot of gravitational potential energy waste when hydraulic excavators work, which seriously affects the efficiency of the whole machine and produces a large amount of emissions. In order to reduce the energy consumption and emissions of large hydraulic excavators which the boom is driven by two hydraulic cylinders, an integrated drive and potential energy recuperation principle is proposed. In the implementation, the original two-chamber hydraulic cylinders are replaced by three-chamber hydraulic cylinders with energy storage chambers, and the energy storage chambers are directly connected with the hydraulic accumulator. The dead weight of the working device is balanced by the initial hydraulic pressure of the hydraulic accumulator, and the gravitational potential energy is directly recuperated. A digital prototype is established for the simulation work to verify the energy-saving effect. Then a test prototype is constructed according to the simulation work. The standard 90° loading duty cycle tests show that compared with the standard hydraulic excavators of the same type, in the case of meeting the same digging force, the working efficiency of the excavator increases by 20.7% and the fuel consumption decreases by 17.1%. In terms of 8 hours of work per day, a single excavator can save fuel up to 47 L per day and reduce carbon dioxide emissions by 123.6 kg.

Keywords: Excavator, Boom, Energy saving and emission reduction, Three-chamber hydraulic cylinder, Hydraulic-gas energy storage drive

1. INTRODUCTION

The large hydraulic excavator working device will accumulate a large amount of gravitational potential energy in the lifting operation. However, the gravitational potential energy is converted into heat energy through the throttling action of the valve and wasted. Statistics show that the wasted potential energy of the medium-sized hydraulic excavator accounts for more than 15% of the whole energy consumption [1], which not only causes huge energy waste but also heats the fluid quickly, affects the continuous operation and causes failure. Therefore, recycling and utilizing the gravitational potential energy has always been an important research direction in the field of mobile hydraulic machines [2]. At present, the main methods include electric hybrid method, hydraulic hybrid method, recovery method based on constant pressure power source, closed pump control recovery method and hydraulic-gas energy storage drive method. The electric hybrid method is to convert the gravitational potential energy into electric energy by the hydraulic motor and the generator [3] then the energy is reused by an electric motor to drive the hydraulic pump [4-6] or the swing of the machine [7]. More than 7 conversions and multiple control links are needed in the whole process of energy recovery and reuse. Although the link of converting gravitational potential energy to electrical energy is omitted with the hydraulic hybrid method [8-10], there are still a lot of conversion and transmission links. In addition, the working device moves fast and the energy conversion time is short. Therefore, the hybrid power units tend to have large power and high cost, and the recovery and reuse efficiency of the gravity potential energy is limited by the number of energy conversion times and the conversion efficiency.

The constant pressure power source system uses a constant high-pressure accumulator as a power source and uses a hydraulic transformer to control the hydraulic cylinder of the working device. When the working device is lowered, the gravitational potential energy is converted and stored in the high-pressure accumulator by the hydraulic transformer [11, 12]. The advantage is that the same components are used for driving and recycling, however the energy efficiency of hydraulic transformers needs to be improved. In Murrenhoff's research, a medium-pressure accumulator is added to the power source and a set of on-off valves are used to replace the hydraulic transformer. By controlling the on-off valve group, the potential energy of the working device can be directly recovered into the same pressure hydraulic accumulator [13, 14]. The system and control methods are more complex.

The closed pump control circuit recovery method is to add an energy recovery closed hydraulic pump connected with the hydraulic accumulator in the closed pump control circuit of the differential hydraulic cylinder. Storing and reusing gravitational potential energy of the working device by coupling with the torque of the main hydraulic pump [15, 16]. Quanlong innovatively integrates the two hydraulic pumps into one, and proposes an asymmetric hydraulic pump with three distribution windows [17]. Only using a single asymmetric hydraulic pump can realize the integrated drive of differential hydraulic cylinder [18] and energy recuperation [19-21]. The asymmetric hydraulic pump is still under further study.

With the hydraulic-gas energy storage drive method, a hydraulic-gas energy storage chamber connected with the hydraulic accumulator is added in the working device drive circuit, and directly recovering and reusing the gravitational potential energy by using the hydraulic accumulator oil pressure balance working device gravity. In the process of energy recovery and reuse, there is only one necessary conversion between mechanical energy and hydraulic energy. In addition, there is no energy-converting component, no limitation of installed power and no intermediate control link. At present, the hydraulic-gas energy storage drive method is the most efficient way to recycle energy, especially for large machines with heavy working devices and high recovery power. And this method is especially suitable for a variety of drive circuits and is easy to integrate into the existing control circuits of the machine. Early research used the method of adding the balance hydraulic cylinder in parallel with the position of the driving hydraulic cylinder to drive the working device [22-24]. The disadvantage is that the structure of the boom, which is the key structural member, needs to be changed. This will affect the service life. Limited by the installation space, this method is only applicable to large and medium-sized machines. Quanlong proposes a three-chamber hydraulic cylinder based on hydraulic-gas energy storage drive principle [25], which integrates energy storage and drive circuits. It can directly replace the original hydraulic cylinder without changing the boom structure. It is suitable for small machines driven by single hydraulic cylinder [26] and large and medium-sized machines driven by two hydraulic cylinders [27, 28]. At present, the team has applied the principles proposed in the boom drive systems of small hydraulic excavator [29] and medium hydraulic excavator [30]. Simulation and experimental research on the operation characteristics and energy consumption characteristics of the boom are conducted [31]. The existing experimental research is based on the small hydraulic excavator, which does not involve the energy consumption of the whole machine during the complete duty cycle. Compared with the small hydraulic excavator, the large hydraulic excavator has a large demand for digging force, and the influence of the hydraulic-gas energy storage unit on the digging force cannot be ignored. Therefore, this paper focuses on the efficient driving of large hydraulic excavator boom with the hydraulic-gas energy storage drive method.

A test prototype is built and the standard 90° loading duty cycle efficiency and fuel consumption are tested.

2. WORKING PRINCIPLE

Figure 1 shows the schematic diagram of a large hydraulic excavator boom hydraulic-gas energy storage drive system. The proposed hydraulic-gas energy storage drive principle integrates the energy storage chamber into the three-chamber hydraulic cylinder, and replaces the original double-chamber hydraulic cylinder by the three-chamber hydraulic cylinder directly. The chamber A and chamber B are the driving control chambers which are connected with the drive circuit. The chamber C is connected to the hydraulic accumulator through the control valve group (valves 1-3) to form a hydraulic-gas energy storage unit for directly recovering and utilizing the gravitational potential energy of the working device.

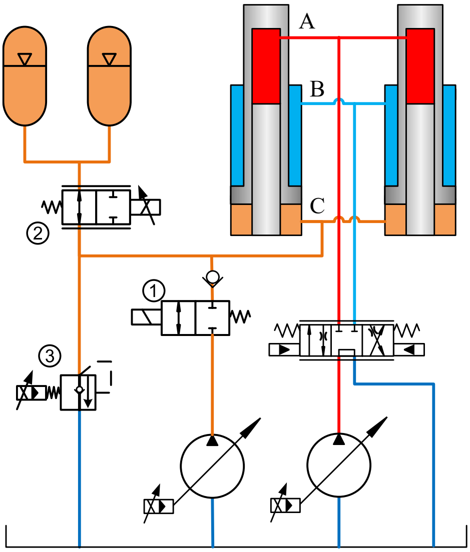

Figure 1: principle diagram of the hydraulic-gas energy storage drive system

The force balance equation of the three-chamber hydraulic cylinder is:

$$p_a A_a - p_b A_b + p_c A_c + \Delta p_c A_c = (m_1 + m_2)\ddot{x} + B\dot{x} + m_1 g + m_2 g \quad (1)$$

When the boom is lifted, Δp_c is a negative value, and when the boom is lowered, it is a positive value. In the equation(1), the gravity of the working device $m_1 g$ accounts for the largest proportion in the load force of the boom hydraulic cylinder. In the working process, the energy consumed by overcoming the gravity of the working device occupies a large proportion in the energy consumption of the whole machine. When the pressure of hydraulic accumulator is set appropriately, the accumulator can basically balance the gravity of the working device as shown in equation(2).

$$p_c A_c = m_1 g \quad (2)$$

$$p_a A_a - p_b A_b = (m_1 + m_2)\ddot{x} + B\dot{x} + m_2 g - \Delta p_c A_c \quad (3)$$

Equation (1) can be simplified according to equation (2). That is, while the hydraulic-gas energy storage driving system is adopted, the driving circuit only needs to overcome the inertial force of the working device, the material gravity in the bucket, and the compensation amount Δp_c of the accumulator pressure change. The energy consumed by the driving system can be greatly reduced. Under conditions of heavy load digging and support of the hydraulic excavator, the ($p_c A_c + \Delta p_c A_c$) in equation (1) generates the force acting upward on the working device, hindering the digging and the supporting. Therefore, the hydraulic accumulator control valve group is designed to disconnect the hydraulic accumulator from the hydraulic cylinder and eliminate the influence of the hydraulic-gas energy storage unit on the digging force and the working condition of the supporting vehicle under the heavy load digging and supporting conditions. When it is necessary to disconnect the hydraulic accumulator from the hydraulic cylinder, the valve 2 is closed. Meanwhile, the valve 3 is opened to make the hydraulic cylinder chamber C have no force. When the boom is lifted, the valve 3 is closed and the valve 2 is opened. At this moment, the hydraulic accumulator is connected with the cylinder chamber C to provide the balance force and release the stored hydraulic energy.

3. SIMULATION RESEARCH

Based on the above theoretical analysis, a digital prototype of the 36-ton hydraulic excavator shown in Figure 2 is constructed. The main parameters of the system are shown in Table 1.

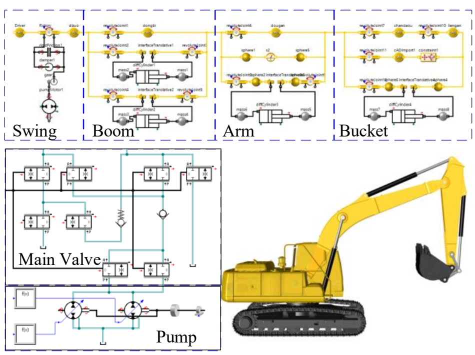

Figure 2: Digital prototype of the 36-ton hydraulic excavator

Table 1: Main parameters of the system

Parameter	Value
Chamber A area A_a	7084 [mm^2]
Chamber B area A_b	7300 [mm^2]
Chamber C area A_c	15601 [mm^2]
Hydraulic accumulator volume V	90 [L]
Hydraulic accumulator pressure p_{c0}	10 [MPa]

The boom operating characteristics simulation results of the hydraulic-gas energy storage drive system and the non-energy recovery system is carried out. Figure 3-4 shows the operating displacement characteristics curve, hydraulic pump output flow curve, and the power characteristics curve of the two systems. During the boom lowering process, the lowering time of the new system is slightly longer than that of the original system, but it has no effect on the actual operation. Since the hydraulic-gas energy storage unit of the new system basically balances the gravity of the working device, the boom could not fall completely rely on gravity. The flow regeneration function is cancelled in the new system so the output flow and power of the hydraulic pump are increased compared to the original system. However, this extra output energy and the gravity potential energy of the working device are both recovered to the hydraulic accumulator and reused when the boom is lifted. So, there is no energy waste. During the boom lifting process, under the condition that the lifting time of the hydraulic-gas energy storage driving system is the same as that of the non-energy recovery system, the output flow of the hydraulic pump is reduced from 500 L/min to 213 L/min, and the output power of the hydraulic pump is reduced from 150 kW to approximately 43 kW, 71% lower.

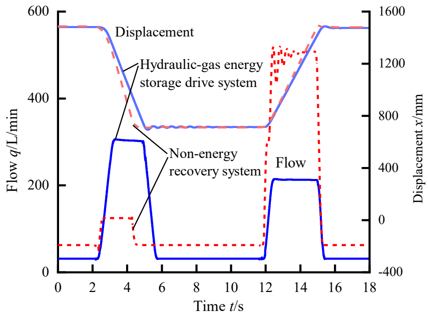

Figure 3: Simulation results of boom operating characteristics

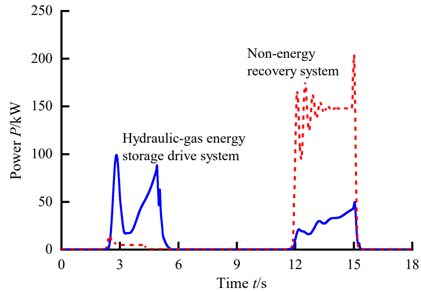

Figure 4: Power comparison between two systems

According to the whole working process, although the output power of the new system hydraulic pump increases compared with the original system, the lifting process has a significant drop. Through the comparison of the total energy consumption obtained from the power integration of the whole working cycle, it is found that the total energy consumption is significantly reduced.

4. TEST RESEARCH

4.1. Test system

A test prototype of hydraulic-gas energy storage driving system is built, as shown in Figure 5. Then the operation characteristics of the system and the energy consumption of the standard 90° loading duty cycle are tested.

Figure 5: Photos of test prototype and sensors

In the test prototype, the displacement of the two hydraulic pumps is 160 ml/r and the rated speed of the engine is 2000 rpm. The Parker SCP-400 pressure sensor is used to measure the pressure of hydraulic pump and the actuator. The HySense QT100 turbine flowmeter is used to measure the output flow of the two hydraulic pumps. The Micro-epsilon WDS-2500-P96 pull-wire displacement sensor is used to measure the displacement of the boom hydraulic cylinder and the arm hydraulic cylinder. The North Micro BW-AH200 gyroscope is used to measure the swing angle of hydraulic excavator. The above sensor data a collected through dSPACE MircoAutobox.

4.2. Boom operating characteristics

For the test prototype with hydraulic-gas energy storage drive system, the displacement of the cylinder and pressure of each chamber when the boom is lifted and lowered for one working cycle are shown in Figure 6.

When the boom is lifted in 3.2s-10.7s, the hydraulic pump and the accumulator supply oil to the chamber A and the chamber C, respectively. The piston rod is pushed to extend. The oil in chamber B flows back to the oil tank through the control valve, and the pressure is maintained at 2.3 MPa due to the action of the control valve. At this time, due to the decrease of oil in the hydraulic accumulator, the pressure in the chamber C is gradually lowered and the pressure in the chamber A is gradually increased to compensate for the decrease of the pressure in the hydraulic accumulator. When braking, due to the large inertia of the working device, after three fluctuations, the boom is stably parked.

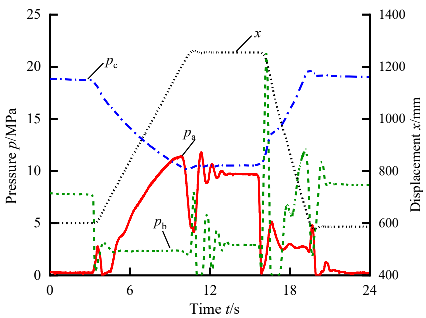

Figure 6: Characteristic curve of boom

When the boom is lowered in 15.7 s - 20.4 s, due to the dead weight of the working device and the pressure of chamber B, the piston rod is retracted. The oil in chamber C is pressed into the hydraulic accumulator, and the oil in chamber A flows back to the tank through the control valve. When the boom starts to fall, the pressure in chamber B rises, pushing the working device to accelerate. As the boom gradually descends, the volume of oil charged into the hydraulic accumulator increases, causing the increase of pressure in chamber C and chamber B to compensate for the increase of the pressure in the hydraulic accumulator.

4.3. Energy consumption characteristics of complete 90° loading duty cycle

In order to further analyse the influence of the hydraulic-gas energy storage driving boom on the energy consumption of the whole duty cycle, a standard 90° loading duty cycle test is carried out on the test prototype. The digging work is carried out continuously. Although there is no clear time limit, it can be roughly divided into four stages: digging, lifting and swing, dumping and return. Figure 7-8 shows the characteristic curve of one duty cycle.

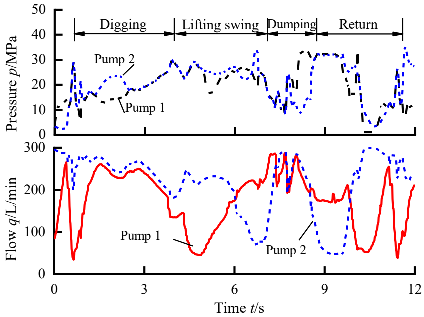

Figure 7: Pressure and flow of the pumps

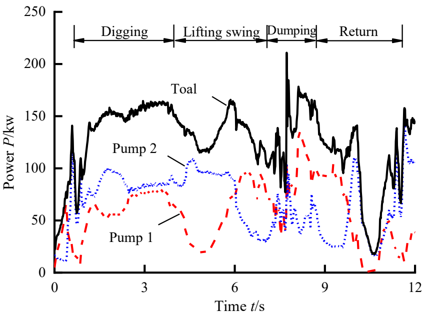

Figure 8: Power of the pumps

In the digging stage, the arm and the bucket are combined to dig, and the boom is assisted by a small range of motion. The combined action condition not only has a large load pressure, but also the output flow of the two hydraulic pumps is about 280 L/min, and the hydraulic power is 75 kW for each pump, reaching the full power working condition.

In the lifting and swing phases, non-energy-saving systems usually need two pumps combined to drive boom and swing, and it will reach full power operation. With the hydraulic-gas energy storage drive system, the flow required for the boom hydraulic cylinder is greatly reduced, which is only provided by the hydraulic pump 2, and the swing is separately driven by the hydraulic pump 1. In this way, the influence of other actuators on the rotary acceleration performance is avoided, and the loss of pressure difference between multiple actuators is also reduced. In this stage, the power of hydraulic-gas energy storage excavator is only 40% of that without energy saving system. Not only the work efficiency is improved, but also the energy consumption is greatly reduced.

In the dumping stage, not only the retraction action of the bucket hydraulic cylinder and the arm cylinder are combined, but also the swing action is present. This is the multi-action compound action so the flow demand is large. However, the load is light so that the total power is not high.

In the returning stage, it is mainly the combined action of boom lowering and swing. The hydraulic pump 1 supplies oil to the swing motor, and the hydraulic pump 2 supplies oil to the boom hydraulic cylinder. The main power consumption is the swinging action, and the power consumption of boom lowering is less.

As can be seen from the above process, when the hydraulic excavator performs a typical 90° loading duty cycle, there is often a compound action of multiple actuators. By adopting the principle of hydraulic-gas energy storage drive system, the output flow of the main hydraulic pump is lower when the boom is lifted because the accumulator basically balances its own gravity. In this way, the hydraulic pump output power is reduced, thus the engine output power is reduced, and the fuel consumption is saved.

In order to further study the working efficiency and fuel consumption of the test prototype, the same test is carried out using a standard excavator with the same type. Two excavators are operated by the same operator. 45 times of 90° loading duty cycle is completed using each excavator. The time and fuel consumption to complete the same work is shown in Table 2.

Table 2: Fuel consumption of 90° loading duty cycle

	Time [s]	Fuel [kg]	Efficiency improvement [%]	Fuel reduction [%]
Standard excavator	577	4.74	-	-
Test prototype	478	3.93	20.7	17.1

Under the same working conditions, compared with the standard excavator, the fuel consumption of the test prototype with the principle of hydraulic-gas energy storage driving is reduced by 17.1%, and the working efficiency is increased by 20.7%. Suppose a machine works 8 hours a day, a single hydraulic excavator can save up to 47 L of fuel per day and reduce carbon dioxide emissions by 123.6 kg. The efficiency is significantly improved while the energy consumption of the whole machine is reduced. The carbon dioxide emission is effectively reduced.

5. CONCLUSION AND OUTLOOK

Based on the large hydraulic excavator driven by double hydraulic cylinders, the principle of hydraulic-gas energy storage drive is proposed. This principle can efficiently recycle the gravitational potential energy during the working process of the excavator boom, and significantly reduce the installed power of the main drive system.

By adopting the principle of hydraulic-gas energy storage drive, the 90° loading duty cycle test results show a 20.7% increase in efficiency and a 17.1% reduction in fuel consumption. The energy saving effect is remarkable.

NOMENCLATURE

p_a	Pressure of chamber A
p_b	Pressure of chamber B
p_c	Pressure of chamber C
A_a	Area of chamber A
A_b	Area of chamber B
A_c	Area of chamber C
m_1	Equivalent mass of the working device
m_2	Equivalent mass of the material in the bucket
x	Displacement of the hydraulic cylinder
B	Damping coefficient of the hydraulic cylinder
Δp_c	Change value of the pressure of the hydraulic accumulator

REFERENCES

[1] Zhang S, Jiang J, Lian G: Research on Recoverable Energy Distribution of Hydraulic Excavator. Joumal of Zhengzhou University(Engineering Science), 2014, 35(2): 120-123.

[2] Quan L, Xia L, Zhao B: Innovation Progress in Research on Gravitational Potential Energy Recovery and Utilization of Hydraulic Driven Mechanical Arm. Journal of Mechanical Engineering, 2018, 54(20): 4-13.

[3] Zhang Y, Wang Q, Xiao Q: Simulation and test of energy recovery for hydraulic motor of hybrid hydraulic excavator. Journal of Mechanical Engineering, 2007, 43(8): 218-223.

[4] Wang T, Wang Q, Lin T: Improvement of boom control performance for hybrid hydraulic excavator with potential energy recovery. Automation in Construction, 2013, 30: 161-169.

[5] Lin T, Huang W, Ren H: New compound energy regeneration system and control strategy for hybrid hydraulic excavators. Automation in Construction, 2016, 68: 11-20.

[6] Zhao S, Zhao J, Li X: Design and simulation on boom energy recovery for hybrid hydraulic excavators. Chinese journal of Construction Machinery, 2016, 14(5): 445-448.

[7] Ochiai M, Ryu S: Hybrid in construction machinery. Proceedings of the 7th JFPS International Symposium on Fluid Power, September 15, 2008, TOYAMA, Japan, 2008: 41-44.

[8] Joo C, Stangl M: Application of Power Regenerative Boom system to excavator . 10th International Fluid Power Conference, March 8-10, 2016, Dresden, Germany, 2016: 175-184.

[9] Casoli P, Gambarotta A, Pompini N: Hybridization methodology based on DP algorithm for hydraulic mobile machinery — Application to a middle size excavator: Automation in Construction, 2016, 61: 42-57.

[10] Xiao Y, Guan C, Li P Y: Optimal design of a compound hybrid system consisting of torque coupling and energy regeneration for hydraulic

hybrid excavator. 2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM), July 7-11, 2015, Susan, Korea, 2015: 1525-1530.

[11] Martin I, Stephan L, Sebastian S: Energy efficient system layout for work hydraulics of excavators. The Twelfth Scandinavian International Conference on Fluid Power, May 18-20, 2011, Tampere, Finland, 2011:46-52.

[12] Shen W, Jiang J, Su X: Energy-saving analysis of hydraulic hybrid excavator based on common pressure rail. The Scientific World Journal, 2013, 2013: 1-12.

[13] Vukovic M, Sgro S, Murrenhoff H: STEAM : a holistic approach to designing excavator systems. 9th International Fluid Power Conference, March 24-26, 2014, Aachen， Germany, 2014: 250-261.

[14] Vukovic M, Leifeld R, Murrenhoff H: STEAM– a hydraulic hybrid architecture for excavators. 10th International Fluid Power Conference, March 8-10, 2016, Dresden, Germany, 2016:151-162.

[15] Chen M, Zhao D: The gravitational potential energy regeneration system with closed-circuit of boom of hydraulic excavator. Mechanical Systems and Signal Processing, 2017, 82: 178-192.

[16] Boehm D, Holländer C, Landman T: Hybrid drives for excavator concepts and solutions. 3th Hybrid drives for mobile machines, Karlsruhe，Germany, 2011: 117-124.

[17] Quan L, Li F: Closed electrohydraulic control system: China, 200610012476.2 [P]. 2006-8-16.

[18] Zhao H, Zhang H, Quan L: Characteristics of Asymmetrical Pump Controlled Differential Cylinder Speed Servo System. Journal of Mechanical Engineering, 2013, 49(22): 170-176.

[19] Ge L, Quan L, Li Y: A novel hydraulic excavator boom driving system with high efficiency and potential energy regeneration capability. Energy Conversion and Management, 2018, 166: 308-317.

[20] Ge L, Zhang X, Quan L: Experiment Study on the Characteristics of Speed-variable Asymmetric Pump Driven Excavator Arm. Journal of Mechanical Engineering, 2017, 53(16): 210-216.

[21] Jing J, Quan L, Huang J: Research on the Characteristics of Asymmetric Pump Directed Controlled Arm Cylinder of Excavator. Journal of Mechanical Engineering, 2016, 52(6): 188-196.

[22] Virvalo T, Sun W: Improving Energy Utilization in Hydraulic Booms - What It Is All about. 6th International Conference on Fluid Power Transmission and Control, March 20-22, 2005 Hangzhou, China, 2005: 55-65.

[23] Chen Q, Li B, Song C: Research on potential energy recycling system of a new hydraulic excavator boom. Journal of Guangxi University: Nat Sci Ed, 2013, 38(2): 292-299.

[24] Ren H, Lin T, Ye Y: Parameters Design and Experiment of Boom Potential Energy Recovery System Based on Balance Cylinder. China Journal of Highway and Transport, 2017, 30(2): 153-158.

[25] Ge L, Dong Z, Quan L: Potential energy regeneration method and its engineering applications in large-scale excavators. Energy Conversion and Management, 2019, 195: 1309-1318.

[26] Quan L, Liang T, Xia L: Control circuit for working device of engineering equipment: China, 201511003769.X [P]. 2015-12-29.

[27] Xia L, Quan L, Zhao B: Research on Hydraulic - Gas Combined Driving System for Hydraulic Excavator Boom. The 10th JFPS International Symposium on Fluid Power, October 25-27,2017, Fukuoka, Japan, 2017: 1-8.

[28] Zhao P, Chen Y, Zhou H: Control Strategy of Hybrid Excavator Based on Torque Prediction. Journal of Mechanical Engineering, 2018, 54(1): 99-106.

[29] Zhao P, Chen Y, Zhou H: Potential energy recovery and energy management strategy of hydraulic hybrid excavator. Journal of Zhejiang University (Engineering Science), 2016, 50(5): 893-901.

[30] Xia L, Quan L, Zhang X: Operating Characteristics and Energy Efficiency of Hydraulic-gas Combined Driving Hydraulic Excavator Boom. Journal of Mechanical Engineering, 2017, 53(20): 176-183.

[31] Xia L, Quan L, Yang J: Research on the Method of Hydraulic-gas Energy Storage Balancing Hydraulic Excavator Boom Weight. Journal of Mechanical Engineering, 2018, 54(20): 197-205.

[32] Hao Y, Quan L, Cheng H: Potential energy directly conversion and utilization methods used for heavy duty lifting machinery. Energy, 2018, 155: 242-251.